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Development of the Interregional I/O Based LCA Method Considering Region-Specifics of Indirect Effects in Regional Evaluation

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Abstract

Background and Aims. Recently, Life Cycle Assessment (LCA) has been recognized as an effective tool for evaluating the environmental impacts of regional activities. The main issue, when applying LCA to region-based studies, is how best to consider and reflect the regional characteristics, as they need to be as close to reality as possible. Several Life Cycle Inventory (LCI) analysis and Life Cycle Impact Assessment (LCIA) studies have been undertaken to study site-specific considerations. However, due to practicalities, very few attempts have been made at identifying the regions affected by regional activities and consider their regional characteristics. Therefore, the purpose of this study is to suggest the direction of a forthcoming study by showing the necessity of regional characteristic consideration in regional evaluation, and to suggest a synthetic, region-based LCA method which can reflect the differences of regional characteristics for direct and indirect effects of regional activities.

Methods. In this study, the Life Cycle Region-specific Assessment Method (LCRAM) was proposed as a new site-specific LCA method. As an example, we used LCRAM to observe the effects of 4 environmental burdens (CO_2, NO_x, SO_x, and SPM) to human health (DALY) in 47 regions (prefectures in Japan). LCRAM consists of a regional database and an analysis method (EIOM). In order to reflect the regional characteristics, including structural (regional production and consumption, interregional trade, and the structure of energy consumption) and environmental features (geographical location, climate, natural conditions, and population density), we first constructed a regional database. This includes an Interregional Trade Matrix (ITM), Regional Environmental Burden Coefficients (REBC), and Regional Damage Factors (RDF). Second, for considering the regional characteristics by using the regional database to the each region, it is a necessary to identify the environmental burden emitting regions (Emitting Regions) of indirect effects due to regional activity. To do this, we developed the Expanded Interregional Input Output Method (EIOM) to take the place of the Multi-Regional Input Output method (Multi-Regional IO) by applying the Two-Regional IO method and the ITM. This is because it is difficult to apply Multi-Regional IO to many regions and industries owing to practical constraints.

Results and Discussion. Upon comparison between the regional database, it was found to show considerable differences due to regional characteristics. It is possible to identify how much the difference of REBC influences the evaluation results by calculating the Deviation Effect Index with REBC and, thus, it was found that the effects from the iron and steel, and electric power industries were more than three times that of other industries. Also the size of RDF varies according to the property of the Environmental Burden (EB) and region; and the more site-specific EB, such as SPM in this study shows, the more distinct the difference. Therefore, it seems reasonable to recommend that the proper regional database is applied to the Emitting Regions. Meanwhile, a comparison with a 9-region IO table (a Multi-Regional IO table made by the Ministry of Economy, Trade and Industry in Japan) was performed to verify the reliability of EIOM. The results indicated a high consistency of over 95%, which verifies that EIOM can be used instead of a Multi-Regional IO method. Finally, as a comparison between LCRAM and Region-Generic Method (RGM) for nine activity regions, we confirmed that the results produced by RGM may be an underestimation or overestimation; as an example, the largest difference among the regions for DALY reached 48% of the RGM result.

Conclusions and Outlook. In this study, it was clearly shown that the evaluation results will be different depending on the structure and environmental features of each region. It is necessary to reflect the proper regional characteristics to evaluate the actual regional activity. LCRAM is an efficient method to consider the regional characteristics for direct and indirect effects to regions, through all stages of the activities. Also, it is possible to apply a regional evaluation for more regions and more detail in the industry classification. Furthermore, it discusses the interdependence and transportation effects due to interaction between the regions. Thus, it may enable us to make an appropriate decision in region-based evaluations such as nourishment and inducement of industry, infrastructure, recycle system, etc. Finally, it is also expected that further discussion and continuous examination will contribute to enabling us to frame an actual and efficient policy based on the regional structural features and environmental features for a sustainable community.

Keywords: Interregional input-output analysis; region specifics of indirect effects; regional database; regional evaluation; regional-characteristic consideration; region-based LCA

Introduction

In building sustainable communities, it has been recognized that there is a need for the consideration of indirect effects (from raw material acquisition, production, transport, and completion), as well as direct effects (from manufacturing and usage stages) within the life cycles of products and services. As such, the Life Cycle Assessment (LCA), a tool used to evaluate environmental impacts, has been used in various fields such as Eco-Design, Eco-Efficiency, Eco-Cost, etc. [1,2]. LCA has also been gaining attention as a method to evaluate regional activities for policy and planning. This can be seen in the use of LCA with Environmental Impact Assessment (EIA) and Strategic Environmental Assessment (SEA). EIA, a general region evaluation tool, is conducted in the execution step of an activity. Because of this, although we find critical problems from EIA's result, it is difficult to prevent the occurrence of those critical problems since the activity has already been started. SEA, which is conducted in the policy and planning steps of the activity, has then been suggested to compensate for EIA's weakness. However, both EIA and SEA only consider the direct effects (on-site) of regional activities. The necessity for the evaluation of indirect effects has now been realized and, as such, LCA has been suggested as a method to do so [3–5]. In addition, there are many cases that LCA is applied to evaluate regional activities, but regional characteristics are almost never considered.

For the site-specifics, Ross and Evans, Lenzen and Wachsmann, Ciroth et al., indicated the importance of using correct inventory data for the regions and circumstances [6–8]. As for the impact, Spadaro and Rabl, and Owens assert the necessity for consideration of different location and emitting conditions [9,10]. Moreover, some researchers proposed a site-specific evaluation method considering the environmental features of the regions [11–14]. Likewise, some studies have tried to consider site-specifics in the inventory and impact, wherein the necessity to diminish uncertainty and to produce evaluations near to reality, has been stressed.

Recently, regional governments in Japan have positively promoted activities that take into account regional characteristics for 'Establishing Recycling-Based Society'. They are particularly interested in a new LCA method (region-based LCA) that can take regional characteristics into consideration. Using LCA with GIS (Geographic Information System), MFA (Material Flow Analysis), and scenario analysis for more direct effects, a regional recycle system and Eco-town was attempted [15,16]. However, it is also necessary that a regional evaluation method can specify the indirectly affected regions and reflect its site-specifics, because the affected regions and effects are different by their regional characteristics. As such, the purpose of this study is to suggest the direction of a forthcoming study by showing the necessity of regional characteristic consideration in regional evaluation, and suggesting a synthetic region-based LCA method which can reflect the differences of regional characteristics for direct and indirect effects of regional activities.

The body of this paper is divided into 3 sections. The features of region-based LCA evaluation range and regional characteristics are discussed in section 1. Section 2 deals with the framework and methodology for a new region-based LCA method suggested in this study. Section 3 describes and discusses the necessity and usefulness of the method.

1 Region-Based LCA

1.1 Features of region-based LCA

A new approach is necessary for region-based LCA to reflect the regional characteristics because the scale, practitioner and subject differ from those of Product LCA as follows. First, for regional characteristic consideration, there are only few times where Product LCA is necessary, since the region of production and consumption is not specified in almost any evaluation cases. While the affected regions are mostly fixed by structural features of a region where the activity is undertaken (the activity region) in region-based LCA, the environmental features differ between regions. Therefore, the main feature of region-based LCA is that it can consider the structural and environmental characteristics of regions that are directly and indirectly affected by regional activity. Especially, to consider the regional characteristics for indirect effects is distinguished from EIA and existing LCA methods. Second, Product LCA, which is mostly used to assess comparatively simple processes, requires evaluation of detailed processes. Region-based LCA, meanwhile, which includes a lot of Product LCA, requires a greater amount of time, cost, and work on inventory analysis. Therefore, in Japan, Life Cycle Inventory analysis (LCI) uses an Input-output (IO) table that has been studied so that it could be an effective solution to high workloads and costs [17].

1.2 Evaluation range and regional characteristics for region-based LCA

In this study, we set and define the evaluation boundary and terms. First, we define the regional level as the prefectures in Japan. This is because the purpose of this study is to assist practitioners in making proper decisions for the policy and planning of regional governments. As seen in **Fig. 1**, regional activities are composed of planning, construction, operation, and completion stages. The effects are largely divided into two parts: the first part being the direct effects (on the left-hand side) – with the environmental burden (EB) emitted to activity regions due to the direct use of the product and energy throughout all stages of the activity; and the sec-

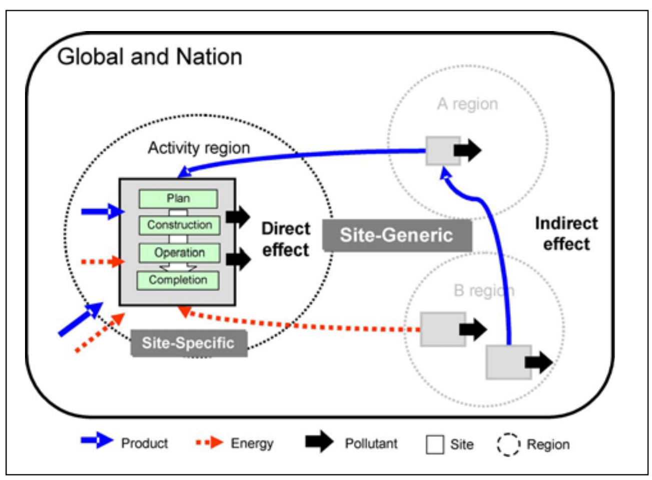

Fig. 1: Approach of Generic LCA method for a regional activity

ond part being the indirect effects – the environmental burden emitted to each region throughout the life cycle of the product and energy which is used directly in the activities (on the right-hand side). As for regional characteristics of the effects in this study, we consider the structural features (regional production and consumption, and trade among regions) and environmental features (such as geographical location, climate, and population density, etc.) at a regional level.

Meanwhile, environmental impact is defined as the damage to all regions which the environmental burden affects. This is not just only the region where the environmental burdens are emitted, because the areas affected are caused by the various impact ranges of the pollutants. Therefore, in this study, the term 'Emitting Regions' is used to describe regions where environmental burdens are emitted, and 'Affected Regions' means the regions which are damaged by pollutant diffusion and secondary effects. Also Emitting Regions are the same as producing regions, because the emission of EB is caused by the production of goods.

2 Life Cycle Region-Specific Assessment Method

It is necessary to specify the emitting sites and to build a regional database reflecting the site-specific structural and environmental features, in order to consider the regional characteristics in region-based LCA as mentioned in section 1.2. However, in considering all effects by regional activity, specifying the emitting sites and building a database of those sites would almost be impossible. Thus, we proposed a new method that includes a concept called 'region-specific', which considers the features of each region, not each site, as shown in **Fig. 2**. The method was named the Life Cycle Region-specific Assessment Method (LCRAM), since it considers the regional characteristics for direct and indirect effects throughout the life cycle of a regional activity.

2.1 Framework of LCRAM

It consists of: regional database, where the characteristics of the Emitting Regions are considered, and an Expanded Interregional Input Output Method (EIOM) which identifies the Emitting Regions through using Interregional Input-Output analysis in order to consider regional characteristics of indirect effects. In section 2.2,3, we discuss the two parts of LIME in detail.

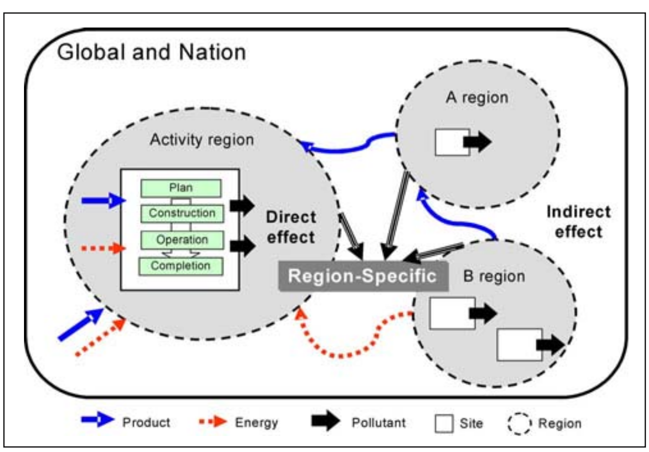

Fig. 2: Approach of LCRAM for regional activity

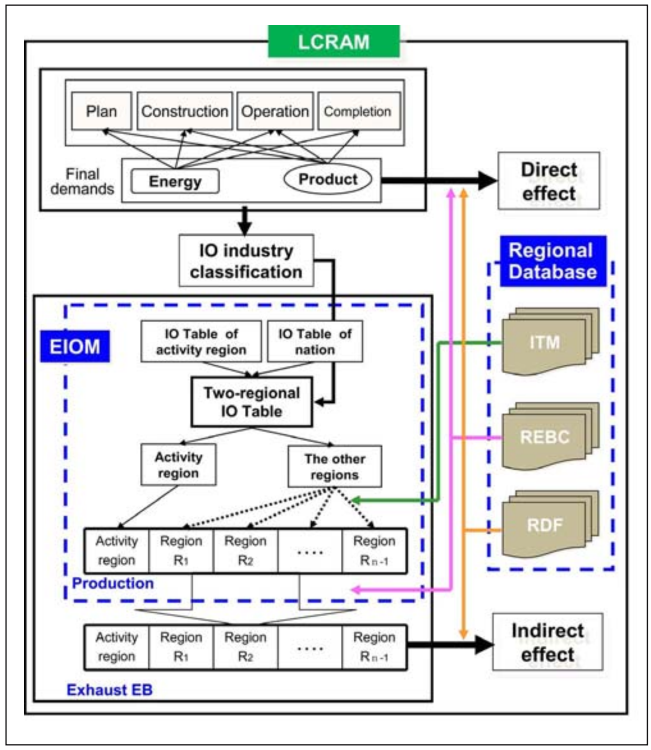

Fig. 3: Framework of the Life Cycle Region-specific Assessment Method (LCRAM)

The flow of LCRAM is shown in **Fig. 3**, and explained as follows.

- List up the final demands (products and energy) that are necessary in each industry for the activity.
- Calculate the direct effects (direct emissions and damages) from the consumption of energy through all stages of the activity in the activity region.
- Classify the final demands according to the Input Output table (IO table) industry classifications.
- Construct a Two-Regional IO table: Two-Regional IO table is made in a method based on the Chenery-Moses input-output model (the general model to make an Interregional IO table) [18].
- Calculate the amount of instigated products in the activity region and the other regions by multiplying the inverse matrix of the Two-Regional IO table by the final demands.
- Identify the Emitting Regions by using the model formula and the Interregional Trade Matrix (ITM) to allocate the instigated products of other regions into n-1 regions (see section 2.3).
- To reflect the structure of regional industry and energy consumption, calculate the environmental burden by multiplying the specified regional production by the corresponding Regional Environmental Burden Coefficient (REBC): (indirect emissions).
- Calculate the indirect damages to the country from the regional activity by multiplying each region's environmental burden by the corresponding Regional Damage Factors (RDFs).
- Calculate the total effects by summing up the direct and indirect effects.

LCRAM finds the direct effects by analyzing site-specific inventory data for a regional activity and considers the indirect effects by identifying the regions indirectly affected with Input-Output analysis. However, we are concerned here with the direct effects, because this study is intended as an investigation of the need for consideration regional characteristics of the indirect effects.

2.2 Regional database

In order to consider the regional characteristics, we constructed a regional database: an Interregional Trade Matrix (ITM) and Regional Environmental Burden Coefficients (REBC) to reflect the structural features, and the Regional Damage Factors (RDF) to reflect the environmental features.

In this study, the necessity for regional data is discussed. It was then constructed for 47 regions (prefectures) and 46 industrial classifications as an experiment. Here, the results are grouped into 9 areas (Hokkaido, Tohoku, Kanto, Chubu, Kansai, Chugoku, Shikoku, Kyusyu and Okinawa) owing to data size.

2.2.1 Interregional Trade Matrix (ITM)

Since the products used in any regional activity are produced in a place besides the activity region, the economical and environmental effects of regional activity also occur in other countries or other regions. We cannot know the instigated production and the EB of indirect effects for each region until we grasp the trade among the regions. Accordingly, we can not use the database, which reflects the regional characteristics, and then consider the regional characteristics in evaluation. Thus, it is essential to grasp the interregional trade structures to identify the Emitting Region and consider the regional characteristics. However, there is no data that directly connects production and consumption. As such, Sample survey and Non survey methods, Gravity model, Entropy maximize model, and Neutral network model, have been used to grasp the interregional trade [19,20]. The strength of the Sample survey method (census data) is that it reflects a real trade feature, but its weak point is that some information is left out (zero sampling) and that it can not consider non-material trade such as service. On the contrary, the non-survey method is able to deal with non-material trade as well as material trade, but the lack of actuality is one of the drawbacks in using this method. Therefore, we tried to make the most use of good points and to make up for the weak points by using a hybrid of Sample survey and Non-survey methods as follows. First, the census data that included real interregional trade information was not used as it is, but instead was used as auxiliary data for the model in order to extract the Trade Deterrence Factors (TDF), showing the relationship between trade and distance. Then, in applying the TDF for the model, we estimated and regulated the amount of trade among the regions, totaling the actual production and consumption of each region.

As for census data of interregional trade in the service industry, no database was found. Thus, we only used traffic census data for daily life to measure interregional trade, because service industry has a strong connection to daily life. As for material movement for agriculture, forestry, fisheries, mining and manufacturing; the physical distribution census, produced every five years by the Ministry of Land, Infrastructure and Transport [21], was used as sample survey data investigating the product movement from the origin to the final destination. However, the origin and destination regions in the census do not always imply the production and consumption regions. Thus, we rearranged it again to take the focus for this study's objection and used it.

The model used, the Entropy Maximizing Model, is one of the Spatial Interaction models which was developed in quantitative geography and now widely adapted to various fields such as city planning and transportation [22]. **Table 1** shows the Trade Deterrence Factor (TDF) for the manufacture, extracted from the physical distribution census data, and the reflection of each TDF on the values estimated by the model.

The results are as follows:

a) Shows the TDFs, which reflect not only the relationship between trade and distance, but also the ease of transportation (e.g. due to size of products) and the distribu-

Table 1: Trade Deterrence Factor and relation with the estimated value for industries

Industry	a) TDF	b) Reflection of TDF (%)	Industry	a) TDF	b) Reflection of TDF (%)
Agriculture	2.054	98.33	**Petroleum/Coal**	1.673	99.17
Forestry	2.413	99.55	**Plastics**	1.383	99.36
Fishery	1.373	97.52	**Rubber**	1.033	98.60
Mining	2.504	99.68	**Leather**	0.889	96.61
Food	1.449	98.81	**Ceramics**	2.703	99.53
Drink and tabacco	2.106	99.47	**Iron and steel**	1.472	99.64
Textiles	1.201	99.46	**Nonferrous metals**	1.372	99.11
Clothes	0.889	96.61	**Metals**	1.886	99.55
Wood	1.852	99.77	**Machinery**	1.340	99.09
Furniture	1.261	97.96	**Electrical instrument**	1.249	98.81
Pulp and Paper	1.291	97.14	**Transport instrument**	1.515	99.30
Publishing	1.929	99.76	**Precision instrument**	1.079	96.59
Chemical	1.315	99.61	**Other manufacturing**	1.383	99.36
			Average	1.562	98.78

tion of industries. Industries with a TDF greater than 1.56 (the average value of all industries) follow the trend wherein, as distance increases, the amount traded rapidly decreases due to its sensitivity to the distance. Examples of these are industries that are evenly distributed throughout the regions, and having difficulties of transportation. On the other hand, industries which are not evenly distributed have ease of transportation display negative gradients less than 1.56. Furthermore, with the TDF for each industry, we estimated the amount of trade among the regions by using the entropy maximize model, so as to verify that the total amount of trade equals the amount produced in each region according to industry statistics.

b) Shows how well the TDF can explain the trade property of each industry by comparing the estimated value with the physical distribution census. As can be seen, the reflection rate is high with an average of over 98%.

2.2.2 Regional Environmental Burden Coefficient (REBC)

Most of Life Cycle Inventory (LCI), Environmental Burden Coefficient (EBC), is national mean data in Japan. In recent years, inventory from Input Output tables has been used as a Hybrid LCA in various fields to compensate for the lack of data and to analyze the inventory efficiently [23]. Above all, it has often been used in region-based LCA for efficiency of evaluation. However, it is necessary to consider the suitability of using inventory data of a national mean for regional evaluations. This is because LCA results vary according to geographical, technological and temporal differences [24,25]. Geographical properties affect the industry structure and technology, as expressed by the difference in energy usage. Also, industry classifications of each region are grouped by the different sub-industries. Therefore, although the industry is the same, the Regional Environmental Burden Coefficients (REBC) can range in value from region to region depending on the existence of energy intensive sub-industries.

In this study, we investigated the differences in REBCs among the regions, caused by the structure of the industry and energy consumption, and looked at the effects on the evaluation results. The differences for agriculture, forestry, fisheries and services industries were not considered since, apart from electric power, the differences among the regions are relatively small. The REBCs of electric power were calculated because the mode of generation and the existence of power plants differ from region to region [26]. For the manufacturing industry, statistics for the manufacturing industry and energy consumption [27,28] (produced by Japan's Ministry of Economy, Trade and Industry) were used to consider the differences. The industries were classified according to the IO table classifications, and then the REBCs were calculated for each industry, this means the amounts of direct emission for EB, such as CO_2, NO_x, SO_x, and SPM from the energy consumption per unit regional production. In **Table 2** the results for iron and steel, and electric power in 9 areas, are shown.

2.2.3 Regional damage factors

Even if the same amounts of EBs are emitted, the effects on the regions differ because of different background conditions such as the geographical location, population, weather, direction of wind, etc. Meanwhile, for LCIA, studies using damage-oriented impact assessment, which evaluate the effects on safe-guard subjects, are actively being carried out [29,30]. Thus, when evaluating the effects, it is necessary to consider the environmental features for site-dependant impacts, such as air pollution, toxicity, and so on. Specifically for human health, LIME (Life cycle Impact assessment Method based on Endpoint modeling, part of the National LCA project in Japan) [31] has made the damage factors, national mean values and regional values (47 prefectures) available to the public for NO_x, SO_x, SPM, and VOC. These factors, calculated by considering the environmental features using a fate model, risk analysis and so on, were used in this study. The Regional Damage Factors (RDFs) not only reflect the damage within the Emitting Region, but the total damage to all regions where the EB is emitted and diffused.

Regional Damage Factors (RDFs) for 9 areas were constructed by grouping the 47 regions into 9 areas and then averaging the RDFs of the regions contained. **Fig. 4** shows a comparison of the RDFs (DALY [Disability Adjusted Life Years] / kg-EB) against the national mean value. The damage appears to differ according to the differences in the EB and the regional characteristics of each region. Particularly in the case of SPM, the effect size depends on the regional characteristics because it has a short range of diffusion and no secondary effects, so that the differences among the regions are considerable. In contrast to SPM, the effect of SO_x is a similar size throughout Japan, except for Hokkaido and

Table 2: Comparison of REBC between the regions for iron and steel, electric power

Region	Iron and steel				Electric power			
	CO_2	NOx	SOx	SPM	CO_2	NOx	SOx	SPM
Unit	**t/million Yen**	**kg/million Yen**			**t/million Yen**	**kg/million Yen**		
Hokkaido	18.74	19.40	16.08	2.63	23.47	20.68	21.33	2.81
Tohoku	2.17	3.01	3.17	0.34	27.24	18.01	13.11	3.25
Kantou	17.09	20.23	17.56	2.79	14.26	7.60	5.30	0.40
Chubu	6.25	7.67	6.62	1.04	21.80	13.95	9.98	2.42
Kansai	11.58	11.89	10.31	1.61	9.56	4.56	2.85	0.21
Chugoku	26.49	30.65	27.80	4.29	35.26	22.63	17.48	4.24
Sikoku	2.70	2.46	2.27	0.29	13.57	11.54	12.00	1.35
Kyushu	31.60	37.85	31.52	5.51	18.22	10.36	6.26	1.79
Okinawa	1.41	2.53	3.08	0.30	43.02	38.23	38.79	5.48
Japan	**15.29**	**17.61**	**15.37**	**2.44**	**18.75**	**11.62**	**8.70**	**1.61**

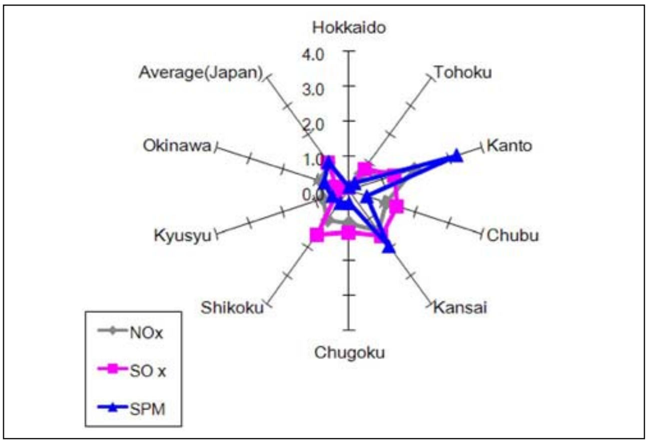

Fig. 4: The comparison of regional damage factors

Okinawa which are separated from the mainland, because the area of effect from SO_x is very wide (with a long range of diffusion and secondary effects). Accordingly, this suggests that we need to use RDF on the Emitting Regions for reflecting regional characteristics in regional evaluation, because the more site-dependant an EB, the more distinct the difference between the regions.

2.3 Identification of the emitting regions

As discussed in section 2.2, the regional database was considered. Even if a regional database reflecting the region's characteristics was established, Emitting Regions (directly and indirectly affected) were not identified; only the national mean-values could be used, such as in generic LCA. Then, whichever regions the evaluations are made for, the results would all be the same. Therefore, it is necessary to identify the Emitting Regions due to regional activity, to consider the regional characteristics for direct and indirect effects. The scope of the direct emission is limited to the activity region. Thus, even in using an existing LCA method, it is possible to consider the regional characteristics for the direct effects by using the regional data - such as the regional electric power inventory or the regional damage factors. Meanwhile, Lenzen's case study showed that the indirect effects occupied a much bigger proportion of the total effects than did the direct effects [32], considering the regional characteristics for the indirect effects should change evaluation results. However, despite recognizing the importance of considering regional characteristics throughout the life cycle, previous studies have not done so since it is almost impossible to identify all Emitting Regions for all indirect products and energy used in all stages of the regional activity. In this study, a method identifying all indirect Emitting Regions was discussed to consider the regional characteristics in regional evaluation, which is the major difference between this study and others performed so far.

To consider regional characteristics for indirect effects in a regional level, we selected the IO analysis method for the following reasons: First, even for indirect products and energy, it is possible to efficiently identify the producing regions by using Interregional IO analysis which can grasp the overall trade tendency among the regions. Second, Regional IO tables for all 47 regions that are appropriate for grasping the regional characteristics and applying regional evaluation have been prepared in Japan [33]. If regional IO tables are not available, the Regional IO can be estimated indirectly by using non-survey methods such as RAS [34,35]. Lastly, we can expect further extension and development of this method because it is able to consider not only the environmental effects, but also economic and social effects as well. In the future, that is an important point for the direction of an LCA for sustainable society construction.

Interregional IO analysis uses the same principle as national IO analysis. However, it can also be used to grasp the structure of interregional interaction since it reflects interregional trade [36].

The domestic input-output model can be formulated as is shown by **Eq. (1)**:

$$X^N = (I - A^N)^{-1} F^N \tag{1}$$

Where, X^N is the domestic commodity output vector, A^N is the competitive import type input coefficient matrix, and F^N is the domestic final demand vector. Similarly, we have the following interregional model given by **Eq. (2)**:

$$\begin{bmatrix} X^1 \\ X^2 \\ \vdots \\ X^n \end{bmatrix} = \begin{bmatrix} I - A^{11} & -A^{12} & \cdots & -A^{1n} \\ -A^{21} & I - A^{22} & \cdots & -A^{2n} \\ \vdots & \vdots & \ddots & \vdots \\ -A^{n1} & -A^{n2} & \cdots & I - A^{nn} \end{bmatrix}^{-1} \begin{bmatrix} F^1 \\ F^2 \\ \vdots \\ F^n \end{bmatrix} \tag{2}$$

Where, X^R ($R = 1,2,\ldots,n$) is the domestic commodity output vector of region R, A^{RR} is the intra-regional input coefficient matrix of region R, A^{RQ} is the interregional input coefficient matrix from region R to region $Q(\neq R)$, and F^R is the domestic final demand vector of region R.

National IO turned out to be the total production (X^N) in the nation without distinguishing regions, whereas Interregional IO can calculate the production instigated in each region ($X^{1\ldots n}$). Furthermore, the emitted EB in each region can be calculated by multiplying $X^{1\ldots n}$ by the corresponding REBC in section 2.2.2.

There are two methods for Interregional IO analysis. One is the Multi-Regional IO method, which considers the relationships between all relevant regions; the other is the Two-Regional IO method, which only considers the relationship between the activity region and all other regions. For application to LCA, the Multi-Regional IO method for many regions with detailed industry classifications (in the case of Japan, 47 regions and 400 industry classifications) is the most ideal. However, with the Multi-Regional IO method, most studies were limited to using only general industry classifications and few regions, because there are many problems such as the increased amount of necessary information, expense, time, and the shortage of information and inclusion of substitute information [37]. Currently, there is a Multi-Regional IO table which has been made for Japan [38]. It is able to specify the Emitting Regions for indirect

effects. However, it is too general, with only rough industry and region classifications (46 industries, 9 areas) to apply to an LCA in this study. Thus, its result is less likely to reflect the proper feature of industries and regions.

On the other hand, the Two-Regional IO method is actually an adaptable method. Its merits are that it is easily able to reflect the regional characteristics by dividing the Emitting Regions into the activity region and the other regions, and applies easily to detailed industry classifications. Richardson asserted that this method can get enough results for use in evaluations that consider regional characteristics [39]. However, this method can not specify other regions into individual regions, only the mean-values could be used for it. Thus, as dependence on external regions increases with trade, the reflection of the results on the regional characteristics decreases. To correct this, we developed a new method that can efficiently divide the other regions into individual regions by using the Two-Regional IO method and regional database ITM. We called this method the Expanded Interregional Input Output Method (EIOM) and it is described as follows:

First, we divide the 47 regions into the activity region T (prefecture T) and the rest of the region S, and then make the Two-Regional IO table using the well-known Chenery-Moses input-output model. The Chenery-Moses input-output model is written as **Eq. (3)** describes:

$$\begin{bmatrix} X^T \\ X^S \end{bmatrix} = \begin{bmatrix} C^{TT} & C^{TS} \\ C^{ST} & C^{SS} \end{bmatrix} \begin{bmatrix} A^T & 0 \\ 0 & A^S \end{bmatrix} \begin{bmatrix} X^T \\ X^S \end{bmatrix} + \begin{bmatrix} C^{TT} & C^{TS} \\ C^{ST} & C^{SS} \end{bmatrix} \begin{bmatrix} F^T \\ F^S \end{bmatrix} \tag{3}$$

Where, $X^{T(S)}$ is the domestic commodity output vector of the activity region T or region S (the rest of region T), $A^{T(S)}$ is the intermediate input coefficient matrix of the activity region T or region S, C^{kl} ($k = T,S$ $l = T,S$) is the interregional trade coefficient matrix with the diagonal element, with c_i^{kl} representing the ratio of a commodity i purchased in the activity region l from the region k. Thus, $C^{TT(SS)}$ plus $C^{ST(TS)}$ equals unit matrix I. Interregional trade coefficients are then analyzed with the assumption that all products within an industry are imported by uniform regional ratio. This is the feature of interregional trade in Chenery-Moses input-output model. And $F^{T(S)}$ is the final domestic demand vector of the activity region T or region S. Then, we can obtain an inverse matrix for Two-Regional IO model **Eq. (4)**, and three effect matrixes as shown in **Eq. (5)**: intra-regional, inter-regional and reflux matrixes [40].

$$\begin{bmatrix} X^T \\ X^S \end{bmatrix} = \underbrace{\left(\begin{bmatrix} I - C^{TT}A^T & -C^{TS}A^S \\ -C^{ST}A^T & I - C^{SS}A^S \end{bmatrix} \right)^{-1}}_{INVERSE\ MATRIX} \begin{bmatrix} C^{TT}F^T + C^{TS}F^S \\ C^{ST}F^T + C^{SS}F^S \end{bmatrix} \tag{4}$$

$$= \left(\underbrace{\begin{bmatrix} (I - K^{TS}K^{ST})^{-1} & 0 \\ 0 & (I - K^{ST}K^{TS})^{-1} \end{bmatrix}}_{REFLUX} \underbrace{\begin{bmatrix} I & K^{TS} \\ K^{ST} & I \end{bmatrix}}_{INTER-REGIONAL} \underbrace{\begin{bmatrix} (I - A^{TT})^{-1} & 0 \\ 0 & (I - A^{SS})^{-1} \end{bmatrix}}_{INTRA-REGIONAL} \right) \begin{bmatrix} C^{TT}F^T + C^{TS}F^S \\ C^{ST}F^T + C^{SS}F^S \end{bmatrix} \tag{5}$$

$$A^{TT} = C^{TT}A^T, \quad A^{SS} = C^{SS}A^S \tag{6}$$

$$K^{TS} = (I - C^{TT}A^T)^{-1}C^{TS}A^S, \quad K^{ST} = (I - C^{SS}A^S)^{-1}C^{ST}A^T \tag{7}$$

The intra-regional effect means the effect of instigating production within the activity region. The inter-regional effect meanwhile, is the effect of the activity on production in outside regions due to inter-regional trade. Lastly, the reflux effect is the effect, due to production in outside regions, of instigating further production within the original region, again through inter-regional trade.

Here, to extract the interregional effect (X^T_{INTER}, X^S_{INTER}) from the three effects it is required to distribute indirect effects in region S into each n-1 region. Thus, we solved the problem by modifying equation (5) as in **Eq. (8–10)**, and extracting the interregional effect (X^T_{INTER}, X^S_{INTER}). We then calculated the input-proportion (P^{ST}), the proportion of the total products produced in region S (X^S) which are imported into region T, as shown in **Eq. (11)**.

$$\begin{bmatrix} (I - \Phi^{TT})^{-1} & 0 \\ 0 & (I - \Phi^{SS})^{-1} \end{bmatrix} \left\{ \underline{\begin{bmatrix} K^{TS}(I - A^{SS})^{-1}C^{ST}F^T \\ K^{ST}(I - A^{TT})^{-1}C^{TT}F^T + C^{ST}F^T \end{bmatrix}} + \underline{\begin{bmatrix} A^{TT}(I - A^{TT})^{-1}C^{TT}F^T + C^{TT}F^T \\ A^{SS}(I - A^{SS})^{-1}C^{ST}F^T \end{bmatrix}} \right\} \tag{8}$$

$$= \begin{bmatrix} (I - \Phi^{TT})^{-1} & 0 \\ 0 & (I - \Phi^{SS})^{-1} \end{bmatrix} \left\{ \underline{\begin{bmatrix} X^T_{INTER} \\ X^S_{INTER} \end{bmatrix}} + \underline{\begin{bmatrix} X^T_{INTRA} \\ X^S_{INTRA} \end{bmatrix}} \right\} \tag{9}$$

$$\begin{bmatrix} \underline{\Phi^{TT}(I - \Phi^{TT})^{-1}(X^T_{INTER} + X^T_{INTRA})} + (X^T_{INTER} + X^T_{INTRA}) \\ \underline{\Phi^{SS}(I - \Phi^{SS})^{-1}(X^S_{INTER} + X^S_{INTRA})} + (X^S_{INTER} + X^S_{INTRA}) \end{bmatrix} = \begin{bmatrix} X^T_{REFLUX} + X^T_{INTER} + X^T_{INTRA} \\ X^S_{REFLUX} + X^S_{INTER} + X^S_{INTRA} \end{bmatrix} \tag{10}$$

$$\Phi^{TT} \equiv K^{TS}K^{ST} \ and \ \Phi^{SS} \equiv K^{ST}K^{TS}, \ F^S = 0 \ then \ C^{TS}F^S = 0 \ and \ C^{SS}F^S = 0 \tag{11}$$

Next, with the proportion P^{ST}, we were able to classify the production instigated in region S into two parts. One is instigated by the activity in region T (X^{ST}), the other is instigated by production in region S (X^{SS}) as demonstrated in **Eq. (12,13)** (Fig. 5).

$$P^{ST} = \frac{[X^S_{INTER}]}{X^S} \tag{12}$$

$$X^{ST} = P^{ST} \times X^{S} \tag{13}$$

As previously stated, the ratio of commodity imported in region T is represented as trade coefficient c_i^{TT} and c_i^{ST}. It is also possible to express c_i^{ST} as $c_i^{S_1T(S_1S)} + c_i^{S_2T(S_2S)} + \cdots + c_i^{S_{n-1}T(S_{n-1}S)}$ as in **Eq. (14)**.

$$X^{SS} = X^{S} - X^{ST} \tag{14}$$

This means that a commodity is imported by the trade ratio $c^{S1T(S1S)}$, $c^{S2T(S2S)}$, $c^{Sn-1T(Sn-1S)}$ from region S_1, S_2, ..., S_{n-1} to region T. As **Eq. (15,16)** indicate, input ratios $ir_i^{S1T(S1S)}$, $ir_i^{S2T(S2S)}$, ... $ir_i^{Sn-1T(Sn-1s)}$, which were extracted by the Interregional Trade Matrix in section 2.2.1, are used for the interregional trade coefficient.

$$c_i^{TT(TS)} + c_i^{ST(SS)} = c_i^{TT(TS)} + c_i^{S_1T(S_1S)} + c_i^{S_2T(S_2S)} + \cdots + c_i^{S_{n-1}T(S_{n-1}S)} = 1 \tag{15}$$

$$ir_i^{TT(TS)} + ir_i^{ST(SS)} = ir_i^{TT(TS)} + ir_i^{S_1T(S_1S)} + ir_i^{S_2T(S_2S)} + \cdots + ir_i^{S_{n-1}T(S_{n-1}S)} \tag{16}$$

Therefore, we can divide the instigated production of region S into individual regional production sites (region S_1, S_2, ... , S_{n-1}): The former (X^{ST}) is distributed into n-1 regions by multiplying by the ratio of region S $r_i^{S_vT}$, from each region (n-1 regions within region S) to region T for each industry. As for the latter (X^{SS}), we distributed into n-1 regions by multiplying by the ratio of region S $r_i^{(S_vS_w)}$, from region S to region S for each industry (**Fig. 5**). This is the same principle as the interregional trade coefficients in Moses and Chenery's IO Model.

As a result, in developing the EIOM, it enables us to identify the emitting regions of indirect effects due to the regional activity for n regions without the use of a Multi-Regional IO table (see Fig. 5).

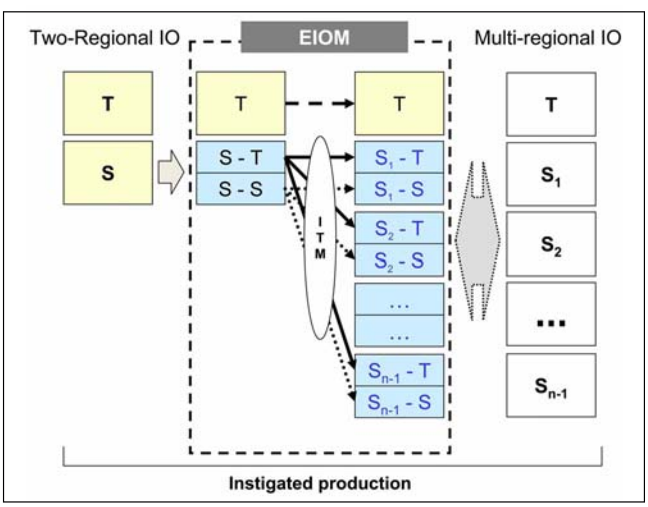

Fig. 5: Conceptual figure of EIOM

3 Results

In this chapter, we discuss the necessity of regional data and the reliability of EIOM, and look into how the region-specific consideration of indirect effects influences evaluation results.

3.1 Examination for regional database and EIOM

3.1.1 Interregional trade matrix

Interregional Trade Matrix (ITM) for each industry (excluding services) was constructed by using physical distribution census data, actual statistics and the Entropy Maximizing model. We then tried to estimate the values that reflect the actual trade property of each industry by using the model and census together in order to make up for the problems in each; i.e. the limit of survey data used in the census and the entropy maximizing model's inability to produce realistic results. As a result, we could avoid counting production for regions where industries are absent, and can theoretically compensate for zero samples according to trade trends. For example, products which are consumed in Tokyo are produced and imported from various regions in Japan. However, the trade feature is widely different according to the distribution, transportation, etc. for the industry. **Table 3** shows input-ratio (include self-supply) against transfer-distance for the consumption of ceramic, rubber, and the total of industries at Tokyo region. As shown in Table 3, Trade Deterrence Factor (TDF) showing the trade property against the distance differs according to each industry. For the ceramic industry, many ceramic products are supplied from surrounding regions at 83.1%; whereas the rubber industry shows trade regions which are of wide distribution, as compared to the total of industries. This is because there are many differences between the industries regarding the distribution of producing regions, ease of transportation, and self-supply of the activity region. It shows that the Emitting Regions differ as to each industry, and that the environmental impact varies according to the Emitting Region's characteristics (structural features and environmental features, see section 2.2) and the distance of transportation. Therefore, to specify the Emitting Regions, it is indispensable to consider the regional characteristics for indirect effects in regional evaluation.

Table 3: Comparison of input-ratio for the product consumption in Tokyo

Industry	Ceramics	Rubber	Total of industries
TDF	2.7	1.03	1.56
Distance	Input-ratio		
km	%		
0–100	83.14	33.20	45.35
100–300	14.78	24.23	29.19
300–500	1.28	25.82	17.01
500–1,000	0.76	13.13	7.34
1,000–1,500	0.03	3.62	1.11

3.1.2 Regional environmental burden coefficients

In this study, the Regional Environmental Burden Cofficients (REBCs) in 47 regions were designed to investigate the differences between the regions and the effects on evaluation results due to the variance in REBCs. **Fig. 6** shows the deviation of REBC (CO_2) and the effect of deviation on the evaluation results for manufacturing industries and electric power. The left-hand side vertical axis indicates the standard deviation of the REBC (Eri)/ average of the REBCs (Emi). From this, the deviation for the machinery, precision instrument and leather industries can be seen to be considerable. As mentioned in 3.2.2, the reason is that the REBCs for each industry can vary widely depending on the region's sub-industry and energy structure.

The Deviation Effect Index (DEI [amount of EB/million Yen]) was considered to find out how much the variance in REBCs affects evaluation results. The DEIs were obtained by then multiplying the above standard deviations by the average REBCs. The DEI, indicating the influence of the evaluation results per unit produced, is shown by the right-hand side vertical axis. As a result, the effect of the machinery and precision instrument industries, which have large deviations, are insignificant, while the Iron and Steel, Electric power, and Pulp and paper industries comparatively have high DEIs, and hence, have a greater influence on evaluation results.

In many studies, national mean values have been used to efficiently evaluate regional activity, because it is very difficult to consider the regional characteristics for each inventory. However, as seen in Fig. 6, it was found that it is necessary to use a regional database reflecting the feature of regional industry and energy consumption to gain a more realistic result. As such, more information should be required for a regional database.

3.1.3 The reliability of EIOM

EIOM was developed to efficiently identify the Emitting Regions for indirect effects in this study. Also the 9-Region IO table (9 area, 46 industries), a Multi-Regional IO table made by the Ministry of Economy in Japan, was used to validate the reliability of EIOM as a benchmark. To do this, the same condition data (interregional trade coefficients) is needed to be used for the examination of reliability. Thus, Two-Region IO tables, used for the reliability of EIOM, were made by grouping the nine regions in the 9-Region IO table into two regions. The instigated production per unit consumption (one hundred yen) in each industry was then calculated using the two methods (9-Region IO table and EIOM) for nine activity regions. It was found that the average correlation between the two methods for the result of nine activity regions, at over 95%, was high. It follows that we confirmed the possibility that EIOM can identify the Emitting Regions for indirect effects instead of using the Multi-Regional IO method. This enables us to consider the indirect interaction between the regions in regional evaluation for applying to many more regions and the details of industry classification. It will also eventually allow us to use the proper regional data for each specified region in regional evaluation. For example, **Fig. 7** shows the results of correlation between 9-Region IO table and EIOM for the Kanto region.

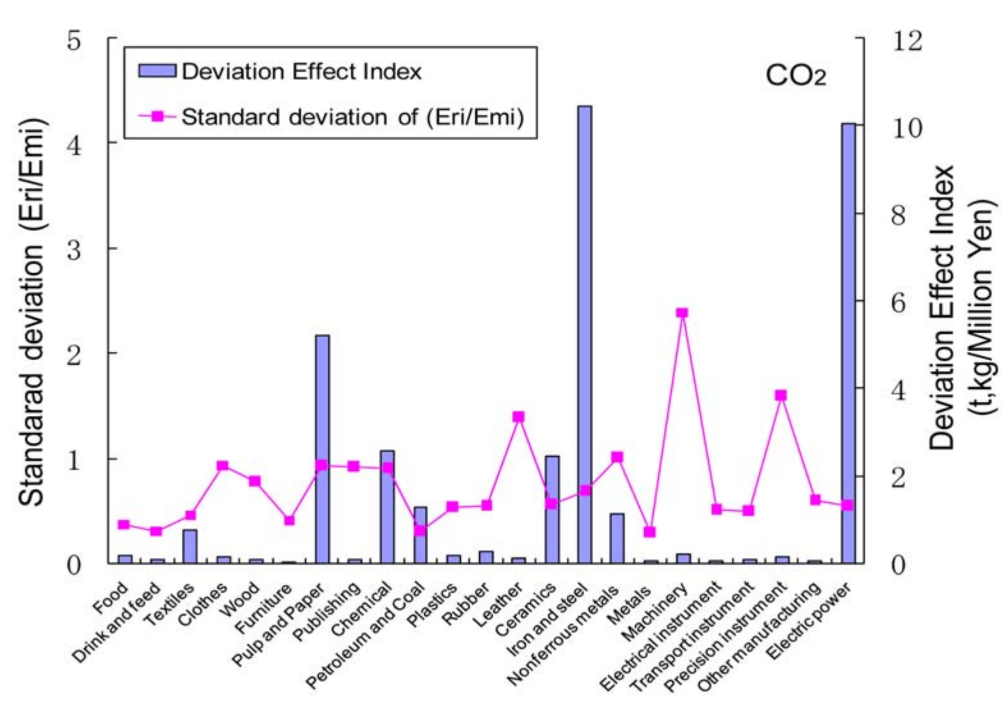

Fig. 6: Deviation of REBC, and the effect of deviation on the evaluation results

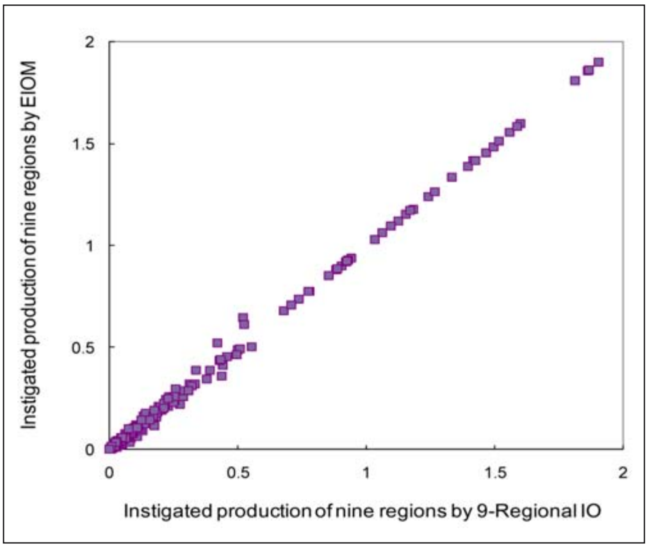

Fig. 7: Correlation between EIOM and Multi-Regional IO (9-Region IO) method for an activity in Kanto

3.2 Examination of regional characteristics consideration for the indirect effects

It was observed in section 3.1 that regional characteristics are widely different in each region. Thus, the result of evaluation is expected to be influenced by considering the regional characteristics. In order to investigate them, we compared the Region-Specific Method (RSM: identifying the Emitting Regions and considering the regional characteristics by use of the regional database with LCRAM or 9-Region IO table) with the Region-Generic Method (RGM: not considering the region-specifics, and instead using the national mean values). We then calculated environmental impacts by unit final demands (one million Yen) in 46 industries for the nine activity regions, and confirmed the difference for the results between them. The emissions for CO_2, SO_x, NO_x and SPM were calculated, and the corresponding damages (DALY) were then calculated by multiplying the emissions by the RDF for human health. In **Fig. 8**, the results are only for indirect effects, since we want to focus on the difference of the regional characteristics and its effects on the results in this examination.

First, the results of RGM can not identify the affected regions by the final demands of activity region. And it differed from the results of the 9-Region IO table, which overestimated by 27% in Hokkaido and underestimated by 20% in Kanto. On the contrary, the result of LCRAM was almost the same as the result of the 9-Region IO table. As it could specify the indirect Emitting Regions for final demands correctly, we could also know the difference of the affected region and environmental impact by the indirect interaction between the activity regions. The dotted line in Fig. 8 represents the results of RGM for comparison against RSM (LCRAM and 9-Region IO table). In the case of comparing the results of LCRAM between Kanto and Hokkaido, it shows a difference of 47% in the RGM result. It points to the possibility that the results show a considerable difference by considering regional characteristics for indirect effects, even though it was the same final demands. Moreover, since an indirect effect is generally greater than a direct effect, the importance is so much bigger.

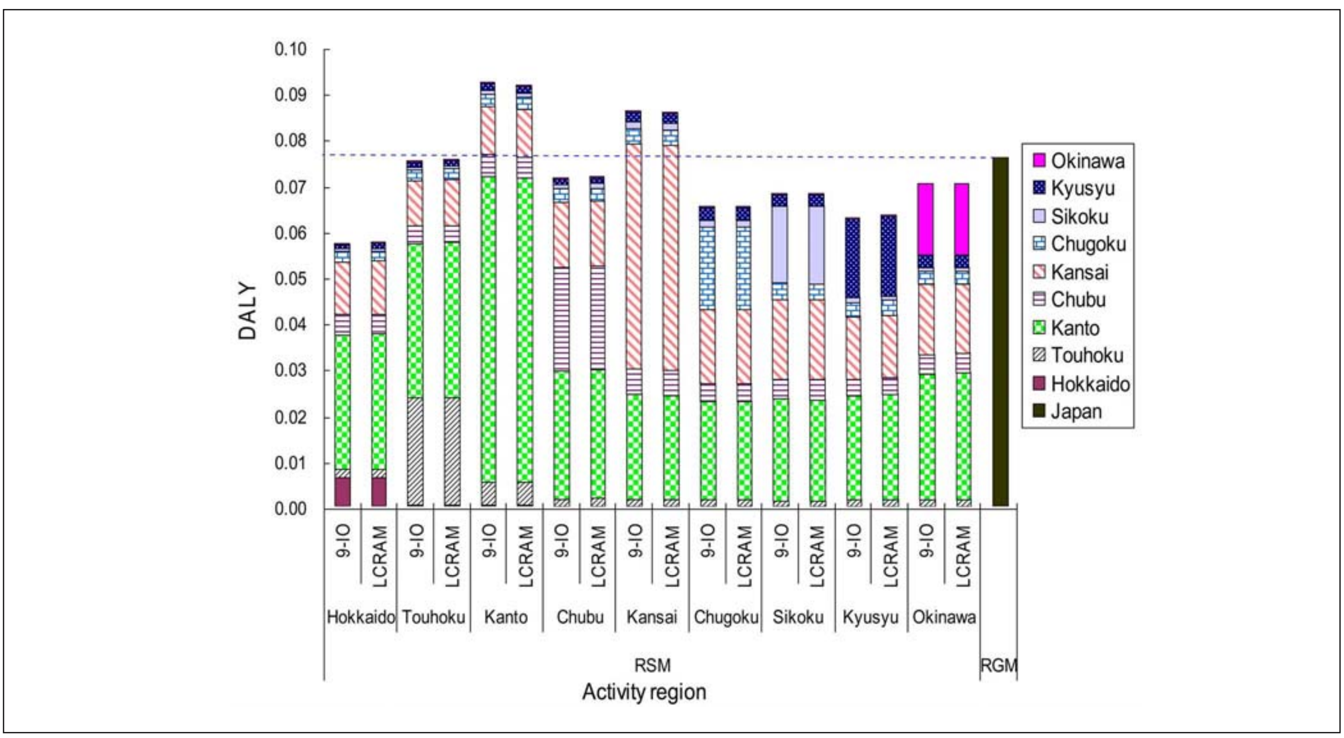

Fig. 8: Relative difference of LCIA results for 9 regions using three methods

4 Conclusions

In this study, we aimed at suggesting the direction of a forthcoming study for region-based LCA by making clear the necessity of regional characteristic consideration in regional evaluation, and developing a synthetic region-based LCA method which can reflect the differences of regional characteristics for direct and indirect effects. Thus, we proposed the LCRAM, consisting of the regional database and EIOM.

First, a regional database was constructed to consider regional characteristics; consisting of an interregional trade matrix, Regional Environmental Burden Coefficients, and Regional Damage Factors. As a result, we confirmed the necessity for region-based LCA to properly reflect regional characteristics, because the results of regional evaluations noticeably differ between the regions. Second, we developed the EIOM, which can identify the Emitting Regions for indirect effects, and verified its considerable effectiveness by comparing it with the 9-Region IO table (Multi-Regional IO table). Finally, an example study, as a comparison between LCRAM and Region-Generic Method (RGM), was conducted to verify the influence of region-specific considerations. The result suggests that region-specific consideration is important for the evaluation of regional activities by showing that the effects of regional activities estimated by RGM may often be an underestimation or overestimation. Also, we could verify that LCRAM enables us to reflect the regional characteristics for the indirect effects of a regional activity, and the reliability and usefulness for it by comparing with the 9-Region IO.

For the reason mentioned above, LCRAM is expected to be applied for the evaluation of various regional activities such as nourishment and inducement of industry, infrastructure, recycle system, etc. LCRAM was also found to have the following benefits:

i) LCRAM can aid proper decisions for regional activities because it can efficiently reflect the characteristics of each region for the direct and indirect effects through all stages of the activity.

ii) LCRAM can quantify the interdependent effects and transportation-effects due to interaction between the regions that have been not reflected in conventional region-based LCA. Thus, we can discuss regional responsibility for environmental effects based on regional consumption of the resources and energies, and apply them to Emissions Trading Schemes for Green House Gas and Waste, etc. at the regional level.

iii) In considering the regional characteristics of indirect effects, LCRAM enables us to apply a regional evaluation for many more regions and the details of industry classification that has been impossible to reflect with an existing Multi-Regional IO method.

In calculating the environmental impact, the economic effects are also known. Thus, we expect LCRAM to also be used to assess the effects such as eco-efficiency and productivity for an activity region.

On the other hand, the following aspects of LCRAM should be improved further: First, in this study we only dealt with 4 EBs, owing to lack of regional database. Especially, it is necessary to construct inventory and damage factors for site-dependant EBs such as heavy metals and chemicals in order to evaluate regional characteristics more totally. Second, a large number of studies have recently been made active based on the regional policies for Establishing Recycling-Based Society such as in 'Eco-Industrial Park' and 'Eco-Town'. In Japan, there are also some studies with MFA and GIS, Environmental Account and LCA for the reduction of energy and material by recycling waste through inter-industrial and inter-regional cooperation [41]. In such studies, it is important to grasp the interaction between basic industries and waste management industries. Above all, to consider the ripple effects by revitalization of waste management an industry such as saving resources and energies, cutting a distance of transportation, etc. is required. Thus, it is necessary to expand the evaluating range of LCRAM. To do these, combining LCRAM with WIO (Waste Input Output model), an analysis model can grasp circulation for the products and waste between basic industries and waste management industries can be applied [42]. In conclusion, it is now also expected that further discussion and continuous examination will contribute in enabling us to frame an actual and efficient policy based on the regional structural features and environmental features for a sustainable community.

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